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Physical Constraints on Models of Gamma-Ray Bursters

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1 Introduction

Gamma-ray bursts are spectacular high energy events. To appreciate this, one can recall how they were discovered [1]. The Vela satellites detected them with their CsI scintillation counters which were sensitive to photons with energies from 0.2 to 1.5 MeV coming from any direction (since these detectors were built to monitor compliance with agreements that forbade nuclear testing in space these instruments were prepared to detect large, unpredictable, bursts of gamma-rays.) When the astronomical gamma-ray bursts appeared, they dwarfed the emission from the rest of the universe, including the sun, by orders of magnitude. These events were hardly expected and barely believable. They would have been taken as instrumental malfunctions if they were not observed simultaneously with separate detectors aboard different satellites.

This highlights the importance of confirmatory observations, especially in the study of erratic, transient phenomena like gamma-ray bursts. It is difficult to build reliable gamma-ray instruments and to adequately understand their response functions. For example, high energy photons can enter the scintillators directly or they can scatter in other parts of the instrument or in other components of the satellite before depositing energy in the scintillators. A mono-energetic, unidirectional beam of photons therefore can generate a broad signal in the detectors. If the response functions are imperfectly known the inferred incident spectra could appear to have bumps or wiggles which are merely artifacts of the deconvolution process [2]. To allow for possible errors of this sort, an observed property of gamma-ray bursts can be considered reliably established only after it has been measured by at least two groups using independent detectors and analysis routines.

This report deals with the constraints that can be placed on models of gamma-ray burst sources based on only the well-established observational facts and physical principles. The next section develops the premise that the very hard x-ray and gamma-ray continua spectra are well-established aspects of gamma-ray bursts. Section 3 summarizes recent theoretical work on gamma-ray bursts with emphasis on the geometrical properties of the models. Sections 4 and 5 describe constraints on the source models which are implied by the x-ray and gamma-ray spectra. The main results are illustrated in Fig. 3 which shows the allowed ranges for the luminosity and characteristic dimension for gamma-ray burst sources. Section 6 summarizes some of the deductions and inferences about the nature of the gamma-ray burst sources. The reader is referred to several recent conference proceedings [3,4,5] and review articles [6,7,8,9] for accounts of other aspects of gamma-ray bursts.

2 Well-Established Facts

A gamma-ray burst source is typically quiescent for one or more years with a flux below the detection level of $\sim 10^{-7}$ erg s^{-1} cm^{-2}. Then, for a 1-10 second interval, Δt, it flares, attains fluxes up to 10^{-4} erg s^{-1} cm^{-2}, fluctuates on time scales as short as 0.01 s, and exhibits one or more peaks (in rare cases Δt can be as short as 0.1 seconds or as long as 1000 seconds). In one case, the burst of 1979 March 5, clear periodic variations were observed; the weak emission after the main peak of the burst was seen to fluctuate with an 8 second period [10]. In the more than a decade since their discovery, several hundred bursts have been detected, but only two sources have been seen to repeat [11,12]. However, the locations of only a small fraction of these sources were accurately determined, and there could have been other repeating sources [66]. In fact, since there are at least hundreds of observable bursts each year, the total number of bursts that have occurred during the history of the galaxy far exceeds the number of galactic neutron stars (the favored candidate for the site of the burst; see below), which implies that each source typically repeats many times.

Figure 1 shows the spectra of several bursts. Here the power per logarithmic bandwidth, P, is plotted against the photon energy E; P = d[power]/d[ln (photon energy)]. This is a convenient plot for theoretical discussions because P peaks in the energy range where most of the power is emitted.[1] (For reporting observations, however, the usual convention of giving the photon flux in photons s^{-1} cm^{-2} keV^{-1} is appropriate since this more closely reflects what is actually measured.) Since the spectra of the gamma-ray burst are known to vary substantially on the shortest time scales for which measurements have been obtainable (0.25 s) [13], the spectra shown here have to be treated as time averages, even for events such as 1972 May 14, 1979 July 31, and 1981 Oct. 16, where the spectra have been measured over different phases of the bursts. Even with this caveat, Fig. 1 illustrates two significant aspects of the gamma-ray burst spectra: the x-ray portions of the spectra rise steeply and the hard gamma-ray parts of the spectra do not show sharp high energy cutoffs. These points will now be examined more closely.

The x-ray spectra below ~100 keV rise steeply with spectral index λ in the range 0.8-1.0 where λ is defined by $P \sim E^{\lambda}$. This property of the x-ray emission is apparent in all the available data: in the OSO-7/IMP-6 [15] measurements, in the Hakucho data [16], in the Apollo 16 data [17] (in this set of measurements the slope of the x-ray spectrum is well determined, but because the location of the source was poorly known, there is ambiguity with respect to its normalization), and in the ISEE-3/P78-1 [18]. The last experiment also measured the x-ray power in the 3-10 keV relative to the total gamma-ray power for three other bursts (1979 March 7, 1979 March 25, 1979 May 4). For these events it was found that this x-ray to gamma-ray ratio was about 0.02, which is consistent with the data shown in Fig. 1.

Accurate measurements of the x-ray spectra of gamma-ray bursts are difficult to obtain because the low energy and high energy parts of the spectra are determined with different instruments, and in some cases different satellites, and because the preponderant gamma-ray flux can be scattered into the x-ray detectors. Nevertheless, the independent determinations by several research groups, and the lack of any reported counter examples, makes the steeply rising x-ray spectra one of the securely determined aspects of gamma-ray bursts. It should be noted that in the experiments where time histories of the bursts were determined, the x-ray flux and the gamma-ray flux varied differently. In all cases the x-ray flux decreased more slowly after the peak of the burst, and in some events the onset of the x-ray flux precedes the onset of the gamma-ray flux [19,65].

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[1] The error limits shown in Fig. 1 represent only the quoted uncertainties in the photon number flux per energy interval. The uncertainties in the photon energy E also contributes to the error bounds for P (by moving the data points along a line of slope two), but this is not shown.

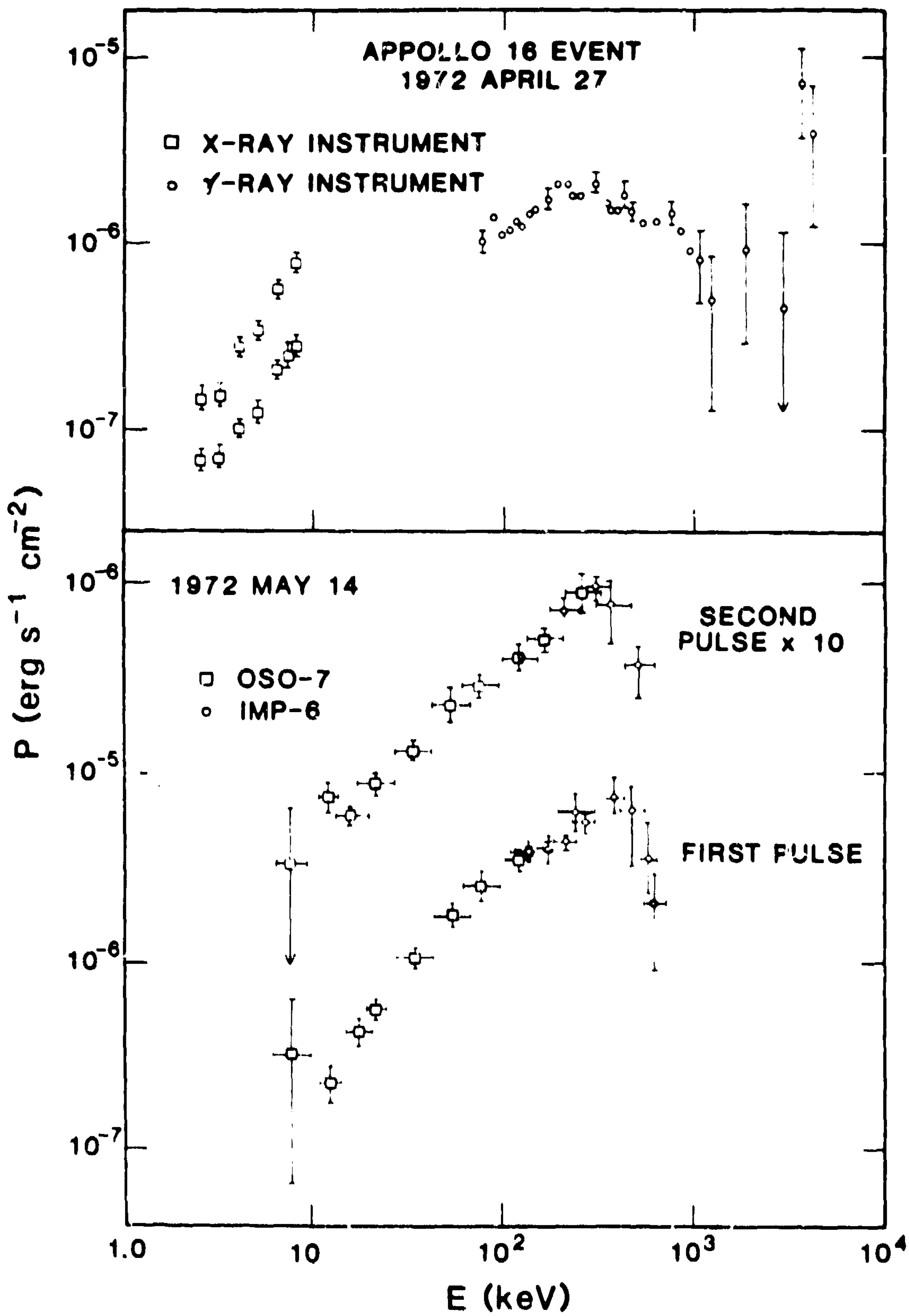
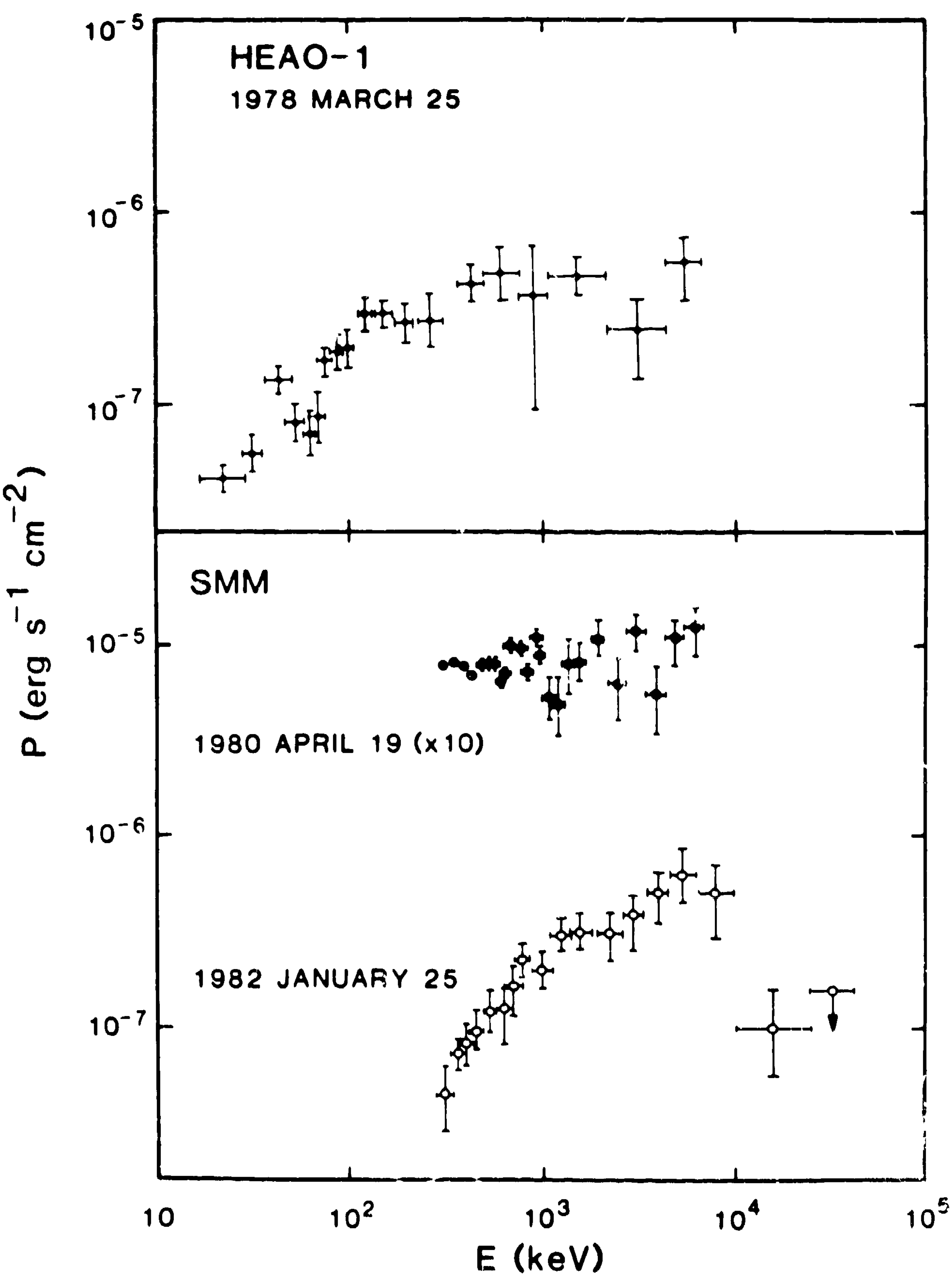


Figure 1. Measured gamma-ray burst spectra which extend down to the x rays or up to the hard gamma rays. The power per logarithmic bandwidth is plotted against the photon energy. The data were taken from References [14-18].



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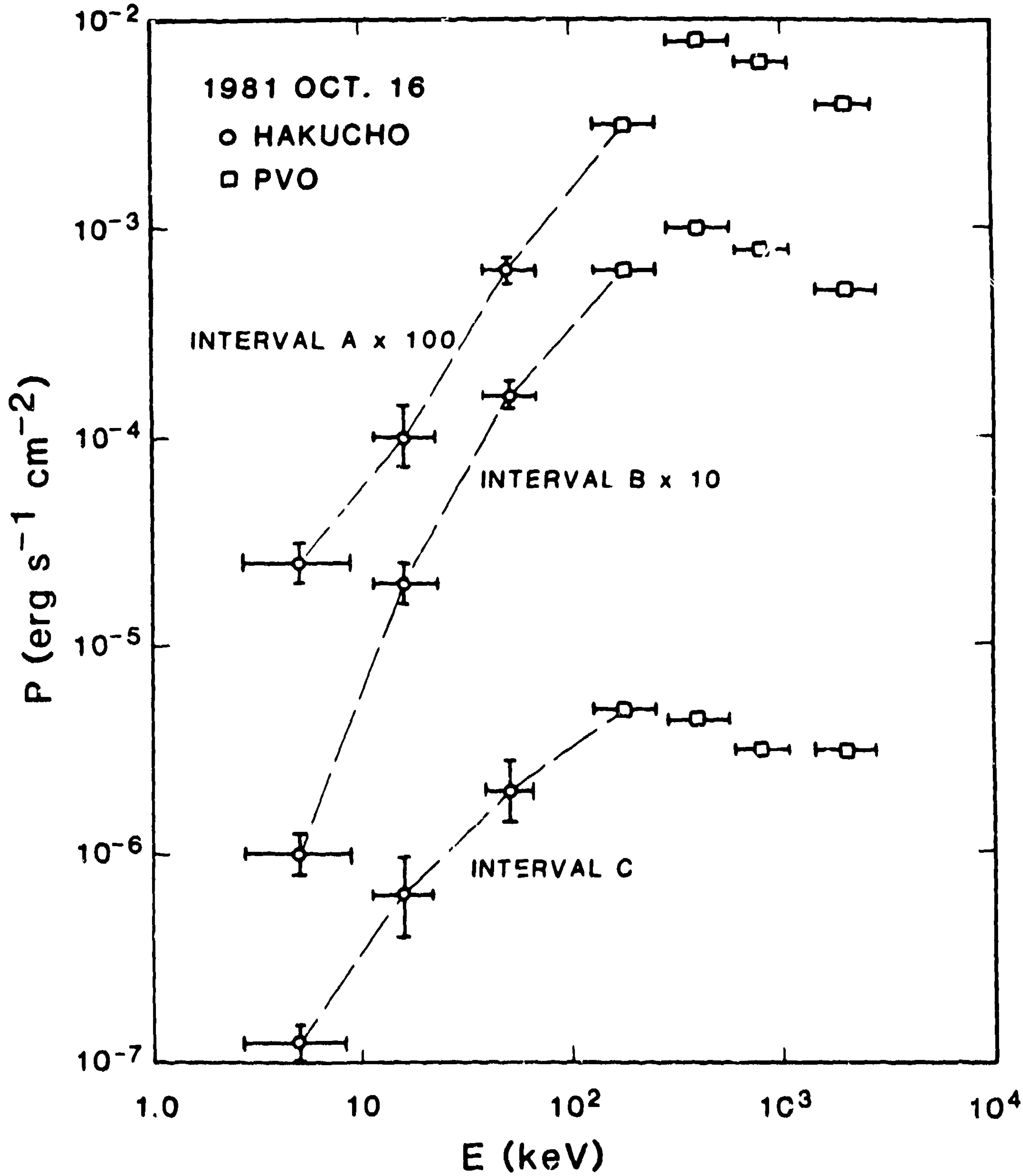

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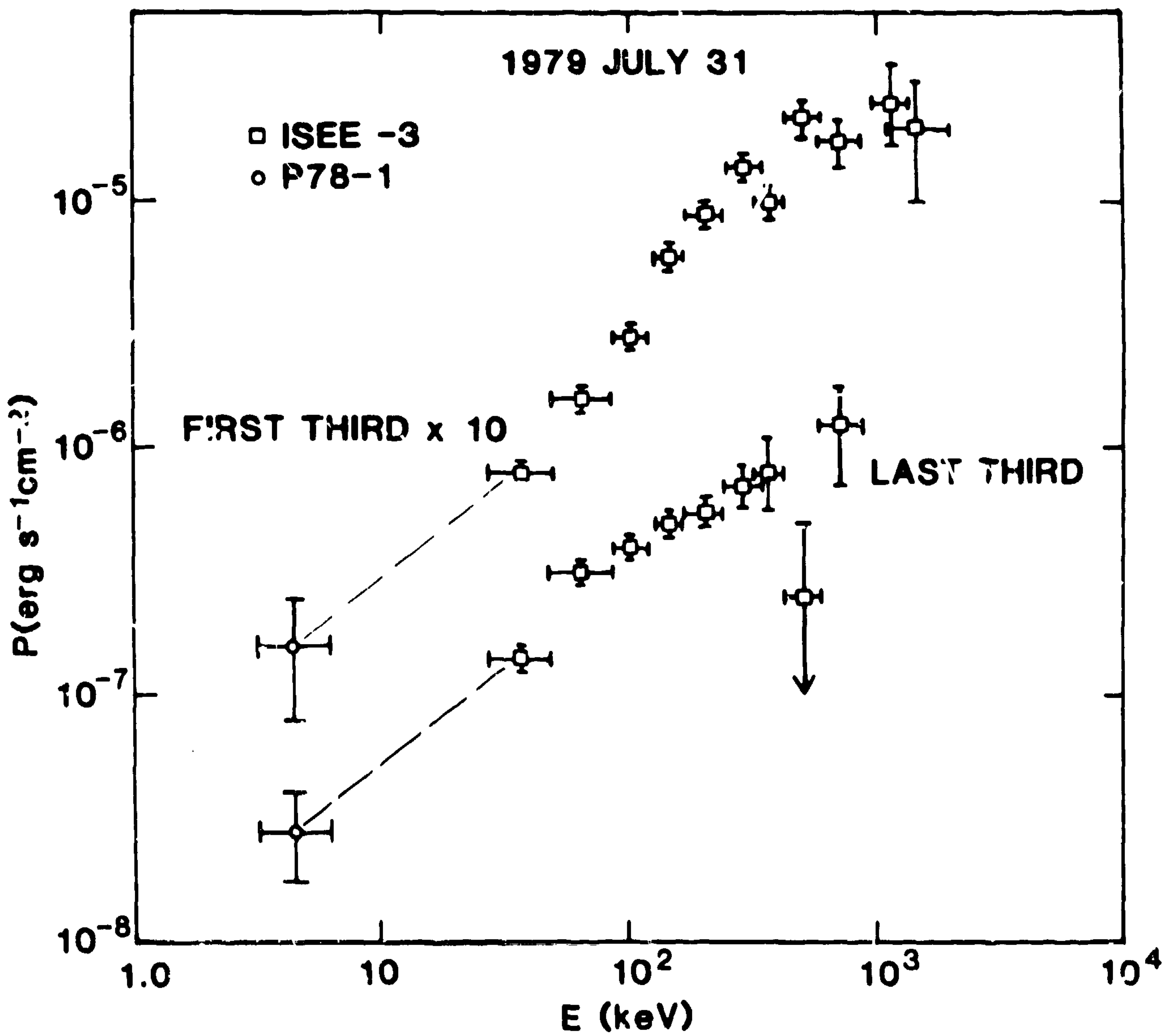

Figure 1. continued

The published spectra from Apollo 16, HEAO-1, and the SMM satellite show that spectra above 1 MeV exhibit spectral indices of $-1 \lesssim \lambda \lesssim 1$. MATZ ET AL. [20] report that the SMM data show that over 60% of the burst spectra have considerable emission above 1 MeV. Furthermore, the distribution of the maximum observable energies is consistent with the photon spectra having power law forms and no high energy cutoffs. Recent HEAO-1 data confirm that gamma-ray bursts commonly radiate above

1 MeV [67]. These measurements supersede the older data which suggested that the spectra were rapidly falling above 1 MeV [6].

There are other aspects of the gamma ray burst spectra that have been reported in the literature, but which cannot yet be considered as "well-established." In their extensive compilation of the Konus observations of gamma-ray bursts, Mazets and coworkers [21,22,23] report that ~7% of the bursts show bumps or emission features near 400 keV and that about a fourth of them show bumps, dips, or wiggles near 70 keV. The high energy features, which are thought of as redshifted 511 keV annihilation lines, were not confirmed by SMM or ISEE-3 observations [2, 24] in two outbursts which were reported to exhibit ~400 keV features in the Konus data. The low energy features reported in the Konus catalog, which have been taken as evidence for cyclotron resonances in a 2-7 × 10^{12} G magnetic field, have yet to be confirmed. On the other hand, the HEAO-1 observations of the 1978 March 25 burst [25] (which was not observed by the Konus experiments) exhibit a 55 keV absorption line and a ~400 keV emission line, and there have been other observations that show suggestions of these features [13, 26, 27], so the question of the existence of "cyclotron" and "annihilation" lines is certainly not closed.

3 Theoretical Proposals

Table 1 summarizes some of the general questions that have been raised in connection with gamma-ray burst sources and some of the proposals for answering them. The only issue for which there is near unanimity is the site of the bursts: nearly all recent theoretical work is based on the premise that the bursts are generated in the vicinity of neutron stars. This agreement has been motivated largely by the observations of the "cyclotron" lines, by the "pair-annihilation" lines, and by the observed 8 second oscillations in the tail of the 1979 March 5 bursts. Since the reality of the spectral features should be viewed with caution, the rallying of theorists around a neutron star model for gamma-ray bursts may be premature, and one should maintain an open mind toward black hole models or other models if they show promise of explaining the spectral and temporal properties of the bursts.

There is no sign of any precipitous rushing to consensus on any of the other issues concerning gamma-ray bursts. Most of the work referred to in Table 1 has appeared in the recent literature and presumably is thought to be in agreement with currently available data (though this do not imply that all of the older theories are incompatible with the newest data or that recent inattention to them necessarily reflects poorly on their merits.) Column three of Table 1 estimates some of the geometric and energetic properties of these explanations. These estimates provide a rough guide to what is implied in the models but, of course, do not fully characterize them. For instance the source region may be highly elongated with one dimension comparable to R (as in [32] and [44]), or the emission from Compton scattering can be nonisotropic if the electrons are outwardly streaming [53]. Despite these caveats, the thrust of Table 1 is that most of the current theoretical discussions are concerned with localized sources of gamma rays which are on or near the surfaces of neutron stars and emit at least 10^{37} erg s^{-1}. Furthermore, the emission is generally taken to be nearly isotropic or at least symmetric with respect to the direction of the magnetic field.

TABLE 1. GAMMA-RAY BURST CHARACTERISTICS

Issue	Explanation	Notes[2]	References
Site	Neutron star	$R \sim 10^6$ cm	[9]
Energy source	Thermonuclear	$r \sim h << R$	[28,29,30]
	Cometary impact	$r \sim h << R$	[31,32,33,34,35]
	Stellar quake	$r \sim R$, $h << R$	[36,37,38,39,40,41]
	Accretion disk	$r \sim h < R$	[42,43,44]
	Gas accretion	$r \sim h < R$	[45,46]
Radiation mechanisms	Bremsstrahlung	isotropic	[16,21]
	Synchrotron	mirror-symmetric	[47,48]
	Compton	isotropic	[49]
	First-order Fermi	isotropic	[43]
	Curvature	beamed	
Source distribution	Thin disk (~100 pc)	$L \sim 10^{37}$ erg s^{-1}	[50]
	Thick disk (~1 kpc)	$L \sim 10^{39}$ erg s^{-1}	
	Large Halo (>40 kpc)	$L > 10^{42}$ erg s^{-1}	[51,52]

[2] R is the stellar radius, r is the characteristic dimension of the gamma ray emitting region, h is the height of this region from the stellar surface, and L is the luminosity in γ rays.

4 The X-Ray Paucity Constraint

As noted above, gamma-ray bursts have steeply rising spectra in the x-ray range and radiate most of their power above several hundred keV. Comparing gamma-ray burst spectra to the spectra from other astronomical sources illustrates how unique these spectra are, especially in the x-ray range. Figure 2 shows spectra from several sources which flare, burst, pulse, or fluctuate. Some astronomical sources produce gamma-ray spectra above a few hundred keV that are not very dissimilar to the gamma-ray burst spectra in this energy range; however, there are no known gamma-ray emitting objects which produce relatively so few x rays. This lack of x rays is a unique signature of the gamma-ray burst spectra and may be a clue to the physical nature of their origin.

Any process which would generate an excessive flux of x rays must be excluded from models of gamma-ray bursts; this is the "x-ray paucity constraint." One such process is the degrading or reprocessing of an intense gamma-ray flux on the surface of a neutron star. Given the luminosities and sizes that are commonly assumed for gamma-ray burst sources, one might expect that a significant fraction of the total emission would be thermalized and would emerge as x rays. A second excluded process is optically thin synchrotron emission from electrons which radiate most of their energy [which takes less than $10^{-15}(10^{12}G/B)^2$ s] before they are reaccelerated. This process produces an x-ray spectrum with a spectral index of about $\lambda = 0.5$ [59], considerably flatter than the observed spectra which have indices between 0.8 and 1.0. Therefore, the synchrotron mechanism as it is usually invoked is incompatible with the x-ray data.

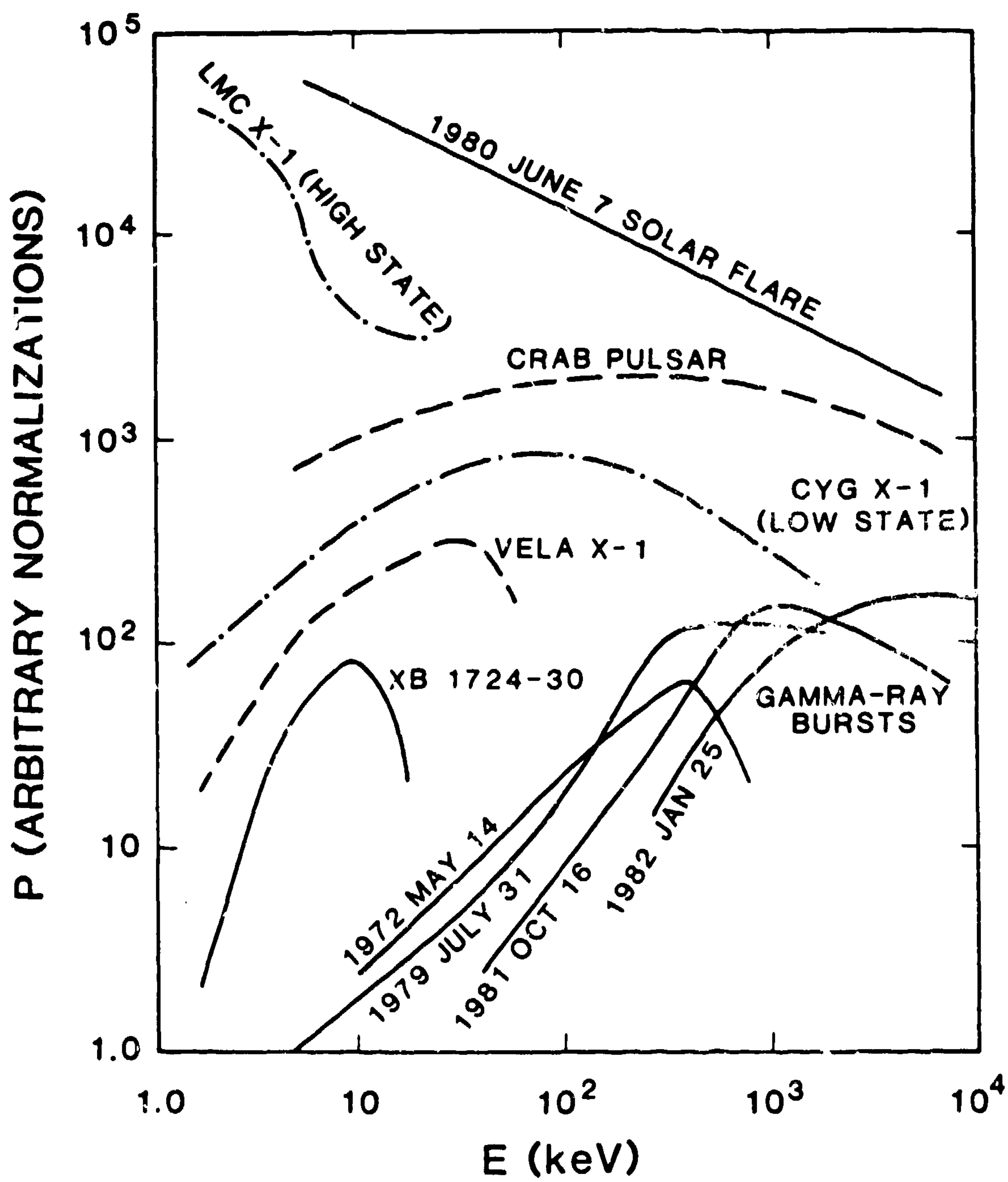

Figure 2. Spectra of various high energy sources. The power per logarithmic bandwidth in photon energy is shown versus photon energy. The vertical displacements of the spectra are arbitrary. Solid lines give the spectra of the bursting or flaring sources [54,55]; the spectrum of the x-ray burster XB1724-30 is shown at its hardest. Dashed lines show two pulsing sources, the phase-averaged emission from the "radio" pulsar (which mostly radiates above 10 keV) in the Crab nebula [56] and the x-ray pulsar Vela X-1 [57]. Dot-dash lines give the spectra of two fluctuating sources which are both black hole candidates, LMC X-1 [57] in its high state (when its spectrum is its softest) and Cyg X-1 [58] in its slow state (when its trum is the hardest.)

These restrictions severely limit the range of physically consistent gamma-ray burst models. A successful model must explain how the energy generated in a burst is radiated with no more than about 2% thermal x-ray pollution. (The observations show that less than about 2% of the power from a gamma-ray burst is emitted between 3 and 10 keV.) The emission mechanism must generate predominately gamma rays with an x-ray spectrum that is at least as steep as $\lambda = 0.8$; i.e., the number of photons per decade of energy should be approximately constant or increasing with energy. Finally, the gamma rays that are generated must not be degraded into many softer x-ray photons by interaction with matter. It is clear that some of the proposed models will have difficulty overcoming the first two requirements, especially models which postulat the burst energy is thermalized in an optically thick region or which involve synchrotron emission. The last requirement, that the reprocessing of the gamma rays does not over-produce gamma rays, depends on the interaction of the gamma radiation with matter; it is thus a topic which falls in the purview of this meeting and is general in that it poses restrictions on the geometry of gamma-ray burst sources which are largely independent of the details of the particular models. We will, therefore, examine this point in some more detail.

The problem of reprocessing gamma rays to x rays can be treated as occurring in two stages: the extraction of energy from the gamma rays and the generation of x rays. Gamma rays incident on matter lose energy predominately by Comptor scatterings on electrons. A photon with an energy comparable to the electron rest mass loses about half of its energy in a single scattering. Fully relativistic Monte Carlo calculations of photons impinging on a stellar surface [60] find that distributions of gamma rays with spectra similar to those observed in gamma-rav bursts deposit more than half of their energy in about three electron scattering depths. These results are insensitive to the incident angle of the gamma rays. The energy that the gamma rays lose can be radiated as x rays or softer photons, or it can drive mass motion; what occurs depends in large part on the rate of energy deposition. For low heating rates the surface temperature is in the UV range; at somewhat higher rates x rays are emitted; and at still higher rates the emerging flux exceeds the Eddington limit and drives mass ejection.

The energy deposited by the gamma rays is eventually reradiated. If the reradiation occurs at approximately the same rate at which the surface is heated, the effective temperature is

$$T_{eff} = (\epsilon F_s/\sigma)^{1/4} \tag{1}$$

where F_s is the incident flux of gamma rays, ϵ is the fraction of the energy that is deposited in the star ($\epsilon > 0.6$) and σ is the Stefan-Boltzmann constant. Equation (1) gives T_{eff} above 1 keV for F_s greater than 2×10^{24} erg s^{-1} cm^{-2}. T_{eff} is a good estimate of the color temperature of the reprocessed emission if the time for the energy to escape from the star is short compared to the duration of the burst and if the time to build up a thermal distribution of photons is short compared to the photon escape time. For a static neutron star surface which is covered with Pop I composition material (as might be expected if the gamma-ray bursts are an accretion phenomenon), the rate at which thermal photons are generated is comparable to their escape rate and more than 99% of the deposited energy is reemitted during the gamma-ray burst if the event persists for more than 0.01 s [60]. The near equality of the thermalization and escape rates suggests that the color temperature of the escaping x rays may exceed the effective temperature. These estimates were made for a nonmagnetic stellar surface. If the surface field exceeds about 10^{11} G, then the transverse motion of 1 keV electrons would be inhibited, and the average photon scattering and emission rates can change by about a factor of two [61].

Gamma-ray burst models can satisfy the x-ray paucity constraint if the incident gamma-ray flux is so low that the peak of the reprocessed emission falls below the x-ray range or is very faint. To estimate the properties of sources that satisfy this constraint, consider the following generic model of a gamma-ray burst source: Take the gamma-ray emitting region to be a distance h from the surface of a neutron star and to isotropically radiate a luminosity L in gamma-rays. The gamma-ray flux that strikes the neutron star surface is approximated by

$$F_s = L/4\pi h^2 \tag{2}$$

and the fraction of the emitted gamma rays that the neutron star subtends is approximated by

$$\delta = (2 + 4\ h^2/R^2)^{-1} \tag{3}$$

which has the correct limiting values for large and small values of h/R.

This is thus a simple two parameter representation of the energetics and geometry of a gamma-ray burster; for most of the published gamma-ray burst models it is possible to find values of L and h which fit into this scheme (see Table 1).

At sufficiently large h or small L the x-ray power in the 3-10 keV band is less than 2% of the total gamma-ray power. Figure 3 shows the allowed region in the (L,h)-plane that is obtained under the assumption that the color temperature is equal to the effective temperature. If the photon distribution is not fully thermalized so that the color temperature exceeds the effective temperature, then the boundary between the allowed and forbidden region is shifted to the right.

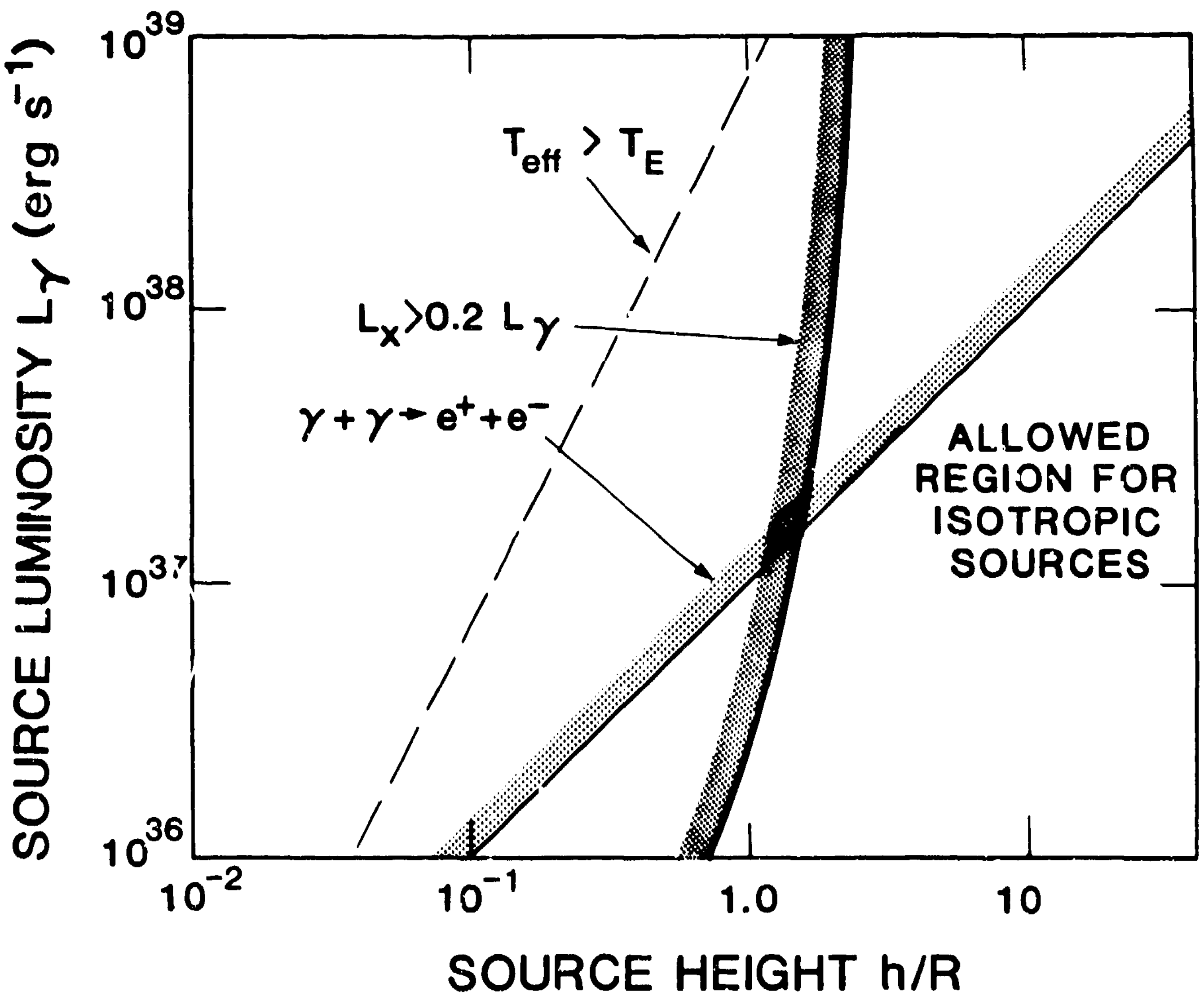

Figure 3. The allowed range of luminosities and sizes for models of gamma-ray bursters which radiate isotropically. This figure is for R = 10^6 cm and $g_{14} = 3$. To the right of the line labeled $L_x > 0.02\ L_\gamma$ (and possibly to the left of the line labeled $T_{eff} > T_E$), the x-ray paucity constraint is satisfied. To the right of the line labeled $\gamma + \gamma \rightarrow e^+ + e^-$, the gamma-ray abundance constraint is satisfied.

The "Eddington temperature" T_E is defined as the temperature for which the black body flux is intense enough to drive ionized hydrogen off the surface of a star:

$$T_E = \left(\frac{3c\ m_p\ g}{2\ \sigma_T\ \sigma}\right)^{1/4} = 1.82\ g_{14}^{1/4}\ \text{keV} \tag{4}$$

where σ_T is the Thomson cross section and g_{14} is the surface gravity in units of

10^{14} cm s^{-2}; for realistic neutron star models g_{14} is of order 1-10 [62]. For large values of L and small values of h the effective temperature of the neutron star surface exceeds T_E, and some of the surface material is radiatively expelled from the star. This expulsion is partially inhibited by the pressure of the incident gamma rays, but it is unlikely that the atmosphere would be static. In these cases the estimates of the reprocessed x-ray flux in a static atmosphere cannot be relied upon since some of the energy deposited by the gamma rays is used to accelerate the escaping matter. The region in the (L,h)-plane where the T_{eff} exceeds T_E is indicated in Fig. 3. In this region a radiative hydrodynamic calculation is required to determine the ratio of the x-ray and gamma-ray fluxes.

5 The Gamma-Ray Abundance Constraint

The observations of photon spectra extending far above the electron-pair production threshold implies that few of the very high energy photons are destroyed in or near the source region by interacting with magnetic fields or with each other. These facts can be used to establish limits on the magnetic field, luminosity, and size of the source region.

The probability of electron-positron pair production by photons of an energy E (in MeV) interacting with a magnetic field rises sharply when the value of the field perpendicular to the direction of photon propagation exceeds about 4×10^{11}/E G [63] (this is for a source dimension of 1 km; if the source dimension is 0.1 km, the field strength estimate is increased by about 10%). If the magnetic field in the source regions were greater than this value and if the low energy gamma rays were emitted over large angles, then many gamma-ray bursts would exhibit spectra that cut off sharply at several MeV. The lack of any indication that the burst spectra cut off below 6 MeV has been used to infer that the source fields are probably less than about 10^{12} G [20]. This limit, while tentative, does not support the contention that the reported spectral features at tens of keV are cyclotron lines.

Two high energy photons can interact to produce an electron-positron pair if the sum of their center-of-momentum energies exceeds the pair rest mass energy. The cross section for this process is of the order of the Thomson cross section. Since the observed gamma-ray burst spectra do not exhibit high-energy cutoffs, pair production apparently does not destroy the large majority of the highest energy photons. To see what type of constraint this implies for the source regions, consider a source region of size r. The density of gamma-ray photons in and near the source region is of the order of $n \sim L/(c\, r^2\, E_p)$ where E_p is a characteristic photon energy defined so that L/E_p is the flux of photons that are energetic enough to produce pairs. The condition that the source regions are optically thin to photon-photon interactions implies that $n\, r\, \sigma_T < 1$ or

$$L \lesssim r\, E_p\, c/\sigma_T \quad . \tag{5}$$

It could be argued that in the source region the gamma rays could be both destroyed and regenerated; however, as the gamma rays escape from the vicinity of the source, they are still subject to photon-photon interactions. If the highest energy photons are not to be destroyed after they have left the source, the source luminosity must obey a relation similar to (5). A detailed study of photon-photon interactions for gamma rays outside of the emitting regions has been carried out taking into account a range of source shapes and spectra and using accurate cross sections [50]. This study showed that for a spherical source which radiates isotropically from its surface the gamma-ray luminosity below 2 MeV must be limited by

$$L \lesssim 10^{37}\ (r/10\ \mathrm{km})\ \mathrm{erg\ s^{-1}} \quad . \tag{6}$$

For $r \sim h$, which is expected for some models (see Table 1), this limit can be displayed in the (L,h)-plane, as shown in Fig. 3. This limit complements the x-ray limits in restricting models which invoke small, luminous, isotropic sources.

6 Conclusions

The relative paucity of x rays in gamma-ray burst spectra coupled with a lack of any observable cutoffs at the high energy end of these spectra, restricts the range of physically consistent gamma-ray burst models. Only a limited fraction of the emitted energy of gamma-ray bursts can be thermalized on the neutron star surface, degraded by synchrotron radiation, or destroyed by photon-photon reactions. If the gamma rays are emitted isotropically, then the source region must be large compared to the size of the neutron star (~10 km) and cannot be very close to the stellar surface. These constraints are summarized in Fig. 3.

The implication is that the sources of the gamma-ray bursts are either large and far removed from the surface of any neutron star or that the emission is beamed away from the stellar surface. If the emission is outwardly beamed, there must be some reason why the observed intensity does not commonly exhibit periodicity due to stellar rotation. Perhaps the magnetic field distributions are azimuthally symmetric about the directions of the angular momenta of the stars so there is no rotation modulation, or the stars are rotating very slowly, or the radiation is radially collimated over much of the stellar surface so the emission pattern is isotropic. The gamma-ray beaming might be produced by electromagnetic acceleration during a disk instability [42-44] or a stellar quake or glitch [36-41] or by radiation interacting with a relativistic (possible pair-dominated) wind [53].

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Discussion

F. C. Michel: If the neutron stars that are the sources of the gamma-ray bursts are extinct pulsars, there would be only $\sim 10^5$ within 300 pc. This tightly constrains what the gamma-ray burst source might be. It is implausible that comets are hitting practically all of these neutron stars so frequently. Also the glitch rate from observed pulsars is too low.

C. B. Boyle: Are there any obvious reasons why the observed optical outbursts do not imply that the γ-ray burst source is not within a binary system.

R. I. Epstein: Gamma-ray reprocessing in a wind [53] or a disk [44] might generate the required flashes.

J. C. Brown: How steep must the low energy slope of P(E) be to agree with the data? I ask this since bremsstrahlung cannot yield P(E) steeper than E^1 and this is possible only if the electron spectra sharply peak at higher energies.

R. I. Epstein: Slopes of 0.8-1.0 are allowed and the optically thin bremsstrahlung process is acceptable in this regard. However, the electron distribution is constrained, and the requirement tht the source be optically thin places severe restrictions on the source geometry [9].

S. Starrfield: How does the 5 March 1979 event fit in with your picture?

R. I. Epstein: If the source of this event is in the LMC at ~55 kpc, its gamma ray luminosity is $\sim 10^{42}$ erg s^{-1}. The restriction based on the $\gamma\gamma \rightarrow e^+ + e^-$ reactions is therefore very severe [64] even though there is no observational evidence for an extensive high energy tail in this burst. These considerations suggest that the source of the 5 March 1979 event is much closer than the LMC or that the emission is highly collimated.